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Application of a Monte Carlo Technique to Model Helicopter Plume Reflections

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ABSTRACT

High fidelity infrared signature modelling of targets requires the accurate representation of not only factors concerned with the target itself but also the immediate environment. Modelling of multiple reflections from extended thermal sources can often be oversimplified, partly due to the complexity of the problem and the resulting intensive processing requirements. The use of Monte Carlo ray tracing techniques for reflection modelling is a documented approach. Insys Ltd has developed a code, McCavity, on behalf of Dstl based on these techniques, to quantify various aspects of the multiple reflections problem to the infrared signature.

This paper reports on the use of McCavity for the assessment of reflections arising from an exhaust plume onto a representative helicopter tail-boom and static rotor structure. A simple, generic, example is used to show that the contribution of reflections from an extended source to the infra red signature can be significant. McCavity code validation against standard published results is also presented.

INTRODUCTION

The Air Vehicle Signatures Group at Dstl Farnborough undertakes and sponsors for MOD, research into the measurement, prediction and assessment of military air-vehicle infra red (IR) signatures. In simple terms, there are two main contributory sources to the IR signature of an aircraft; the first comes from the plume and is therefore a direct consequence of the powerplant system, and the second comes from the airframe itself. The signature arising from the airframe is primarily attributed to thermal emission and surface reflections. The surface can become heated through several mechanisms, including aerodynamic heating, conduction from internal hot sources (electronics, powerplant), plume impingement and solar absorption. Plume impingement is a particular problem for helicopters, the effect of which can be seen in Figure 1, where the airframe structure is seen to be heated by the plume.

High fidelity IR prediction models are dependent on the accurate representation of the thermal and radiation processes. This requires appropriate definition of the target geometry, material properties, heat sources and the influence of the surrounding environment. Accurate representation of surface temperatures is particularly important and a vital element of the prediction process. At Dstl advanced CFD solvers and thermal modelling tools are employed to provide the thermodynamic data for aircraft exhaust gases and surface heating. These include SAPPHIRE [1], MuSES, FLUENT and PHARO [2].

The platform thermal characteristics determined by such models can be imported into radiation models, which can also determine the environmental influences on the platform. One such code, CAMEO-SIM, has an advanced synthetic scene generation capability, and has been the topic of previous GTMV papers [3, 4, 5]. CAMEO-SIM is used to generate radiometrically accurate images based on thermally embedded targets within an environment and is used to provide an accurate assessment of EO camouflage systems. However, CAMEO-SIM is currently limited to solid targets; consequently the associated plume is not calculated as a source and therefore reflections from this source are not modelled. For helicopter signature prediction this can be a particular limitation in the medium waveband. For example, Figure 2 shows an IR image in which a plume reflection can be seen on the main rotor blade. For such platforms, reflections arising from the high temperature and area of the powerplant have the potential to contribute significantly to the overall platform signature.

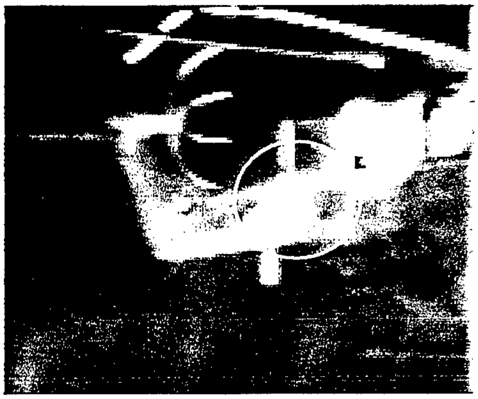

Figure 1 Measurement IR image showing tail-boom heating due to impingement of plume

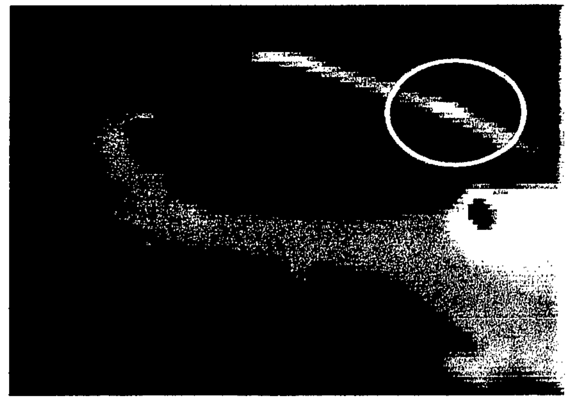

Figure 2Measurement IR image showing a strong plume reflection on the rotor structure

Dstl has recently investigated the ability to model such reflections through the use of a separate IR prediction system known as McCavity. McCavity is an IR solver for a discrete target. The system has been specifically designed to import unstructured CFD solutions and hence can take full account of platform plume and thermal characteristics. McCavity, developed for Dstl by Insys Ltd, combines advanced ray-tracing algorithms with a statistical Monte Carlo approach to simulate complex multiple reflections. This technique enables the interactions between thermal emissions, radiative heat transfer and surface-to-surface reflection phenomena to be predicted accurately. A flow diagram of the modelling process is summarised in Figure 3, indicating the role of McCavity with respect to the other codes.

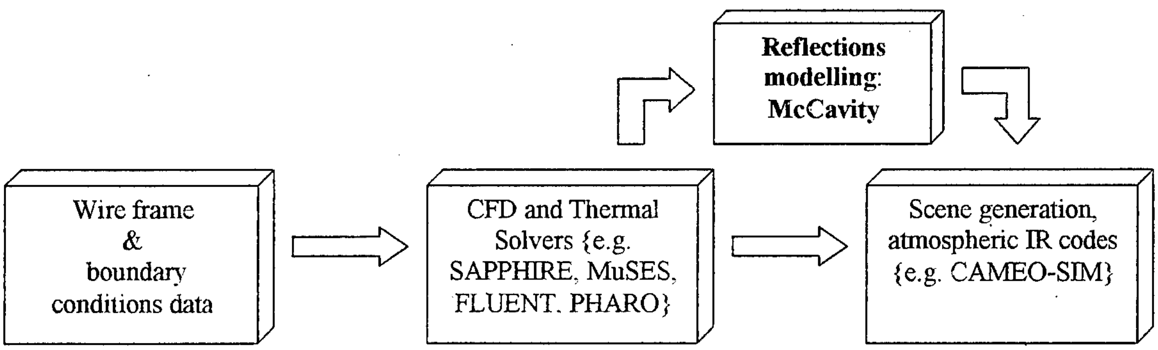

Figure 3 Flow diagram showing McCavity with respect to other modelling codes

This paper provides a brief introduction to McCavity, and the ongoing validation process is discussed. Validation against two standard published results is presented. These along with other similar simple validation test cases are providing a high degree of confidence for application of these techniques for IR signature reflection assessments. As a capability demonstration, the reflections arising from the exhaust plume of a generic helicopter are modelled and presented.

THE McCAVITY CODE

McCavity uses a Monte Carlo stochastic radiation prediction algorithm to determine the properties of the infrared signature for a discrete target. The Monte Carlo method is not discussed in detail as it has been extensively covered elsewhere [6, 7, 8]. The target to be modelled is imported with appropriate thermal and optical properties assigned to each of the individual facets either as a surface description (wire-frame) or a volumetric grid (as produced by CFD codes). The optical surface characteristics are defined with reference to the bi-directional spectral reflectance distribution function (BRDF) and/or the spectral hemispherical directional reflectance (HDR).

In general reflection modelling is dependent on the accurate calculation of view factors, F_{IJ}, between facets and gas cells. The view factor is generally defined as [8] the fraction of radiant energy leaving surface I of area, A_I, that is intercepted by surface J of area A_J, where,

$$A_I F_{IJ} = \int_{AI}\int_{AJ} \frac{\cos\theta_I \cos\theta_J}{\pi r_{IJ}^2} dA_I\, dA_J \qquad (1)$$

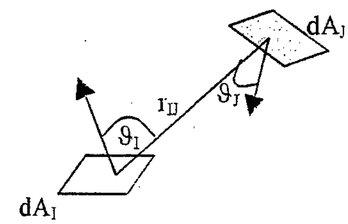

Figure 4 Schematic of view factor between two surfaces

However, this exchange term requires a directional factor to be introduced to account for non-lambertian reflections and emissions, as described in general terms by the BRDF function (which in a non-spectral form would be a 4-D function). In addition, facet to facet shadowing will need to be taken into account in some geometries. The consequent mathematical expressions are, except for simple cases, intractable for any analytical solution. Accordingly the favoured approach is to adopt a numerical integral.

In some cases, codes have been developed to solve using a radiocity solution with a fixed number of bounces. Here a Monte Carlo solution has been adopted which ensures that the appropriate number of reflections is fully accounted. This is particularly important for enclosed systems such as cavities, where many bounces are required to form an accurate solution. There are several different approaches to such problems, including analytical techniques, projection methods as well as Monte Carlo ray tracing algorithms. Emery *et al.* [9] provides a discussion of these in terms of potential accuracy and calculation times and concludes the Monte Carlo method probably represents the best numerical method for computing view factors for complex surface interactions. A study for Dstl conducted by Rolls Royce [10] drew similar conclusions, which led to the specification for McCavity.

The prediction method involves the generation of a statistically large number of random rays simulating the emission of photons either to or from the facet and gas cells. To account for directional emission for the solid surfaces the simulated emission has a weighted directional function applied to the random direction generator of the rays. Similarly the reflection properties are weighted such that the overall integral of a large sample of random rays will converge to the BRDF function. The gas cell radiation is treated isotropically. These rays are individually tracked using conventional geometric ray tracing techniques. The evolution of each ray is determined through another statistical assessment at each interaction for either an emitted or reflected energy contribution. The individual ray trace process halts when either the ray is absorbed by a facet or strikes an element of the image plane.

CODE VALIDATION

Validation of McCavity [11] has been an integral component of code development through rigorous testing at every stage. The code has been compared with several analytical solutions in the open literature to provide fundamental confidence in the computational accuracy. The accuracy of calculations performed by McCavity are controlled by three factors:

(i) The number of rays employed,
(ii) The numerical precision of the calculations, and
(iii) The accuracy of the input conditions of the problem under investigation.

The accuracy to a certain extent can be refined through increasing the number of rays employed and the detail within the initial model; however, this can drastically increase the processing requirements. There is always a compromise between confidence in the results and sensible processing times. Nominally accuracy at the 98-99 % level is expected from the Monte Carlo method with a practical number of rays.

Two examples presented here using simple cavity geometries with diffuse optical properties. The accuracy in the geometric representation is high, and therefore the numerical precision of McCavity is under investigation. The published analytic solutions were programmed into a test harness for comparison purposes with McCavity. After obtaining a high degree of confidence in the test harness McCavity was run to the same input conditions with favourable results.

Sparow and Jonsson [12] examined the radiant emission characteristics of diffuse conical cavities and presented the efflux of radiation from a cavity opening. The apparent hemispherical emissivity (AHE) for a conical cone with angles ranging from 25 to 180 degrees is presented for emissivities ranging from 0.3 to 0.9. Figure 5 shows the geometry and a comparison between the McCavity results (symbols) and the analytic based test harness (line). They agree to within a 1.5 % error margin and for angles greater than 40° this is within 0.5 %. An error on the order of 2% is expected due to the statistical nature of the McCavity analysis method.

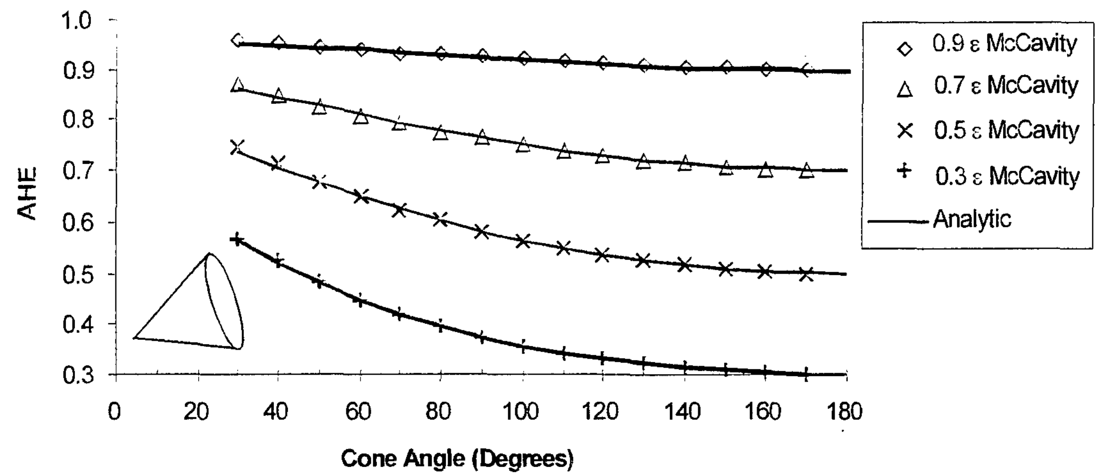

Figure 5 Comparison of apparent hemispherical emissivity (AHE) for an analytical solution [12] of a diffuse conical cavity with McCavity at emissivities of 0.3, 0.5, 0.7 and 0.9

Additionally, the apparent emissivity distribution along the cone surface was compared for a cone with semi-angle of 45 degrees and emissivity of 0.5; the results are shown in Figure 6. There is very good agreement between the analytical solution and McCavity, with the exception of points near the apex. This is considered to be due to an instability in the mathematics of the analytical solution, McCavity is not susceptible to this.

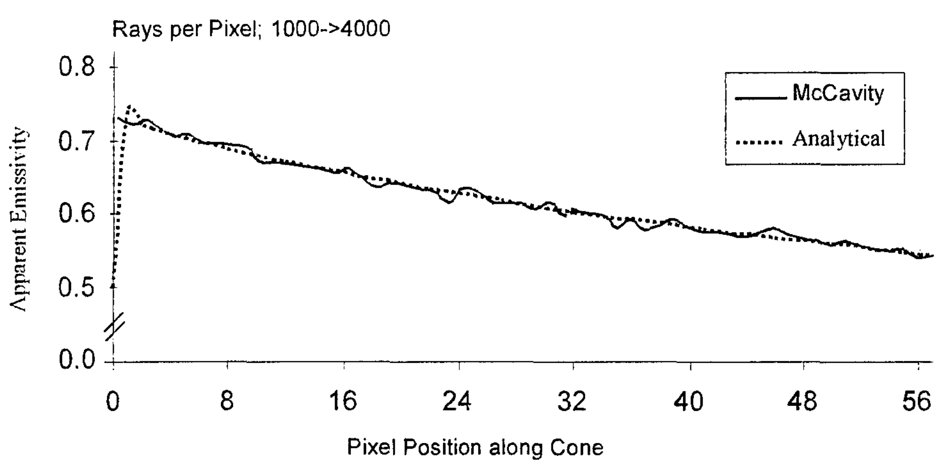

Figure 6 Comparison of Apparent Emissivity obtained analytically [12] for a diffuse conical cavity with McCavity at emissivtiy 0.5 and semi- angle 45 degrees

Similar comparisons have been made with Bedford and Ma's [13] analytic calculations, who examined the emissivities of diffuse cavities, for isothermal and non-isothermal cylindro-cones. A geometrical representation of a cylindro-cone, which consists of a cylinder with parallel sides and a conical end section, is shown in Figure 7.

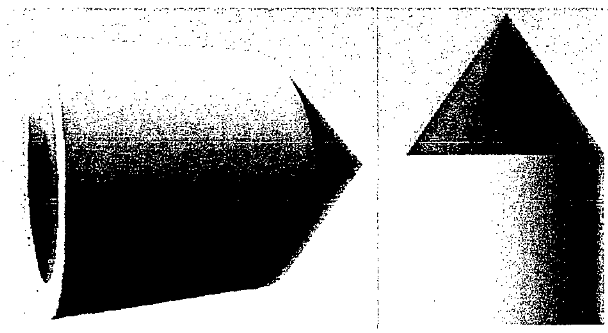

Figure 7 Geometric representation of a cylindro-cone [13]

The half-angle of the conical end piece was varied and the apparent hemispherical emissivity obtained both analytically as detailed in [13] and with McCavity, the results are shown in Figure 8. The agreement was seen to be excellent with less than a 1 % difference between the analytic solution and McCavity.

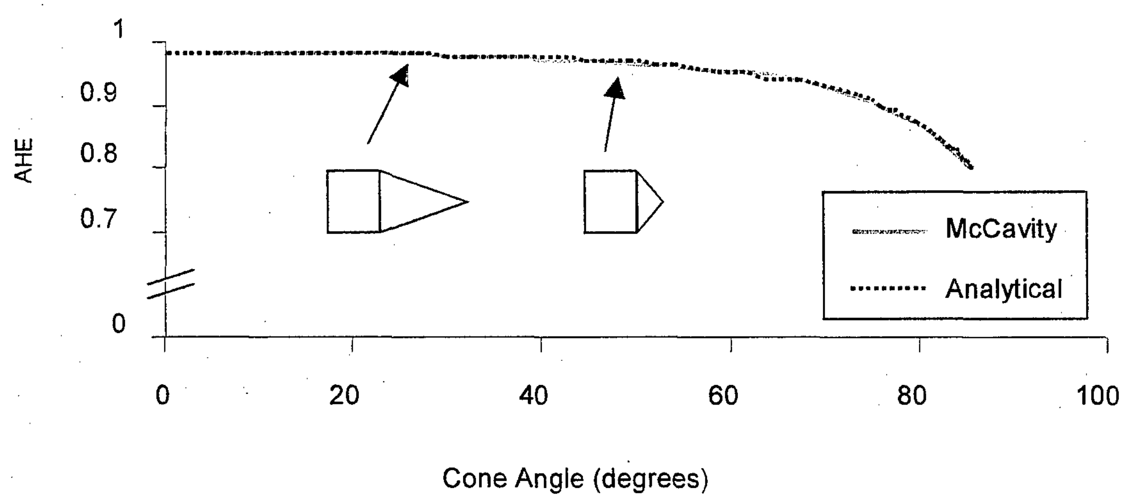

Figure 8 Comparison of apparent hemispherical emissivity (AHE) obtained analytically [13] with McCavity for increasing cone angle at an emissivity of 0.5.

Repeating the McCavity calculations would yield a normal distribution of values. In the presented examples the mean value converges toward the analytic solution. Additionally increasing the number of rays is expected to produce similar results in closer agreement to the analytic solution. The agreement shown here between the analytic solution and McCavity provides confidence in the McCavity algorithm. For more complex geometries and volumetric grids the accuracy is restrained by the input fidelity and the number of rays employed for a functional computation time. The optimisation of these are part of an ongoing validation programme.

EXTENTED SOURCE REFLECTIONS

As a capability demonstration, McCavity has been used to highlight the influence of reflections arising from a helicopter exhaust on a tail-boom and rotor structure. The three-dimensional CFD geometry generated for this study is shown in Figure 9, where the mass inlet boundaries used to represent the exhaust and down-wash are also indicated. Meshing was performed using a tetrahedral mesh with a sizing function based around the exhaust inlet. For this assessment arbitrary flow conditions were modelled. A fixed down wash velocity at (16 m s^{-1}), corresponding to a mass flux of 19.6 kg m^{-2} s^{-1}, was used to produce impingement of the exhaust plume onto the boom structure. The exhaust was defined with the initial boundary conditions representative of a 'top hat' exhaust gas at velocity 95.4 m s^{-1} (i.e., mass flux, 117 kg m^{-2} s^{-1}) and temperature, 596 K. Appropriate values for the principle IR emitting gas species, CO_2, H_2O, within the plume were also applied to the exhaust inlet.

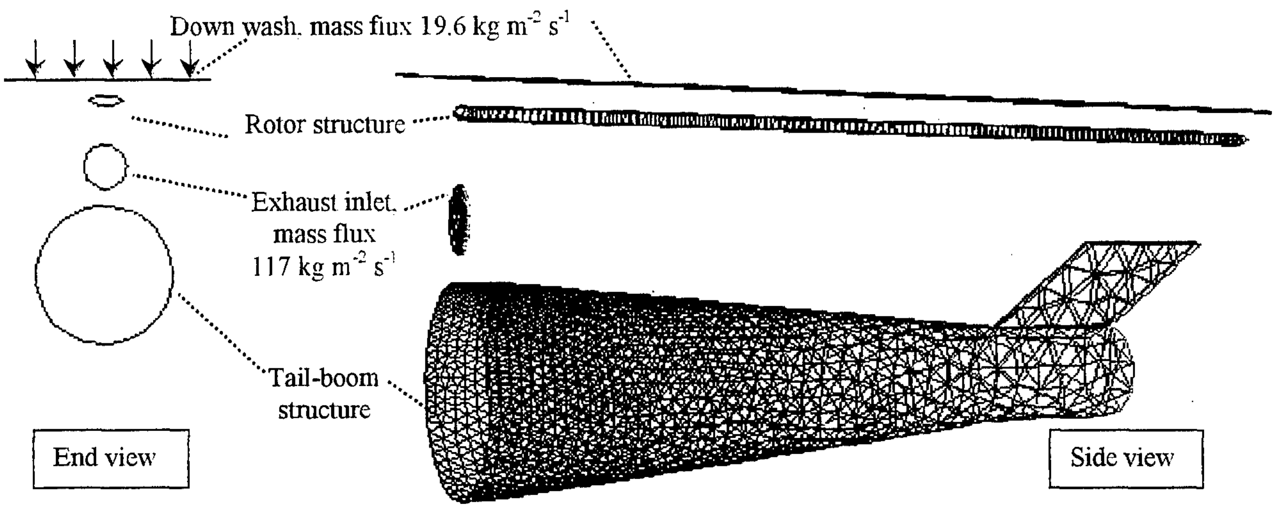

Figure 9 End and side view of a representative helicopter tail- boom and rotor structure with mass inlet boundaries shown

The CFD analysis was performed using FLUENT 6 with the K-ε turbulence model. The rotor flow was treated as a simple down-wash inlet with a static rotor blade defined just below this. The results obtained with the solver are presented in Figure 10. Image (a) shows the gas temperatures of a slice taken through the mid-section of the y-axis, demonstrating the plume clearly being directed down over the tail-boom structure. Image (b) shows the velocity vectors for this same slice; a concentration occurs in the proximity of the rotor structure due to a more detailed mesh. The temperature profile on the solid surfaces is shown in images (c) and (d) for two different views. Heating is experienced on the tail-boom with the majority occurring towards the rear of the structure. The final image (d) shows the underside of the rotor blade structure. There is no heating in evidence on the blade, as expected, since this component experiences no impingement from the plume.

Results from the CFD analysis were subsequently imported into McCavity to perform a reflection assessment. The material optical properties were defined as a 50 % diffuse, grey reflector uniformly across all the solid surfaces. The calculation was performed for the wavelengths 4 to 5 microns. Plots of radiant intensity [W sr^{-1}] output by McCavity are shown in Figure 11. The first image (a) shows the overall signature including contributions from both the plume and solid surfaces. The plume is visible due to the radiated emission of the hot species within it. The impingement-heated component of the tail-boom is also clearly visible. In addition to these two sources a reflection component is also included in this total image. These components are also presented separately for clarity. Image (b) shows the signature without the plume contribution. The plume component is presented in (c) and finally the reflected component only is shown in (d). Comparison between this reflected component and Figure 10(c) shows the addition of a high intensity region located along the top of the tail-boom, below the position of the exhaust plume. This demonstrates the contribution of reflections from the plume. A number of areas have been marked on these images and used for spectral analysis, which follows.

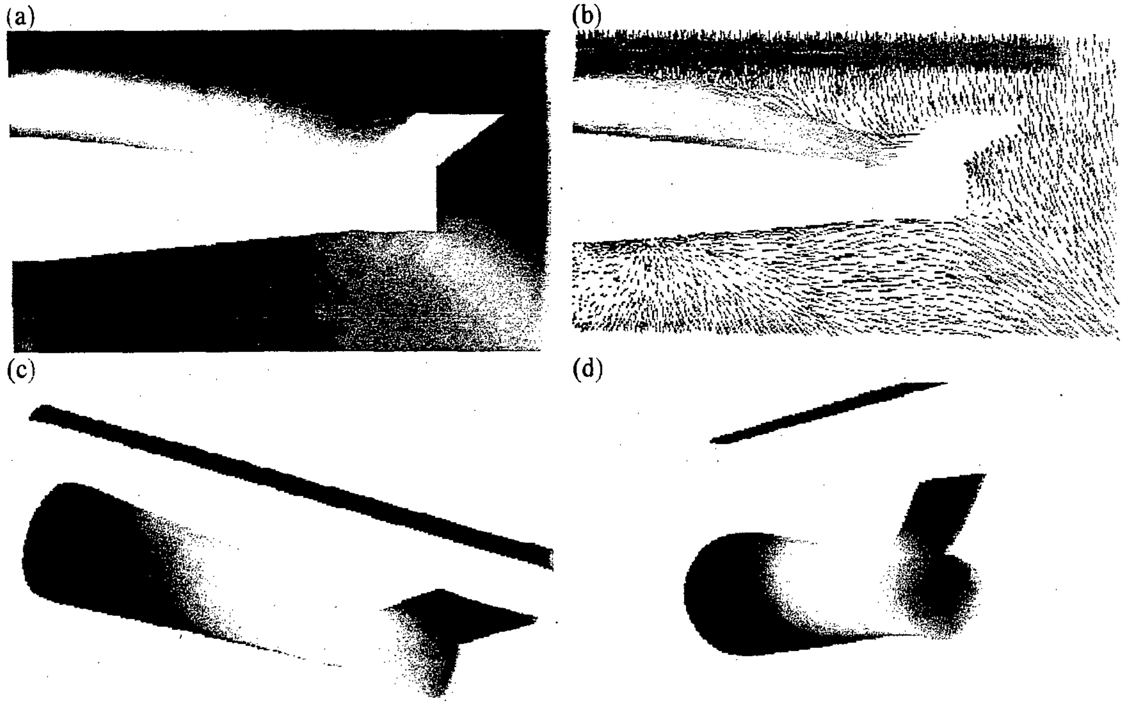

Figure 10 Temperature (K) profile of FLUENT CFD solution, (a) slice through central y-axis showing gas temperature, (b) central y-axis slice showing velocity vectors, (c) view down onto the helicopter tail-boom, (d) view up towards the underside of the rotor blade.

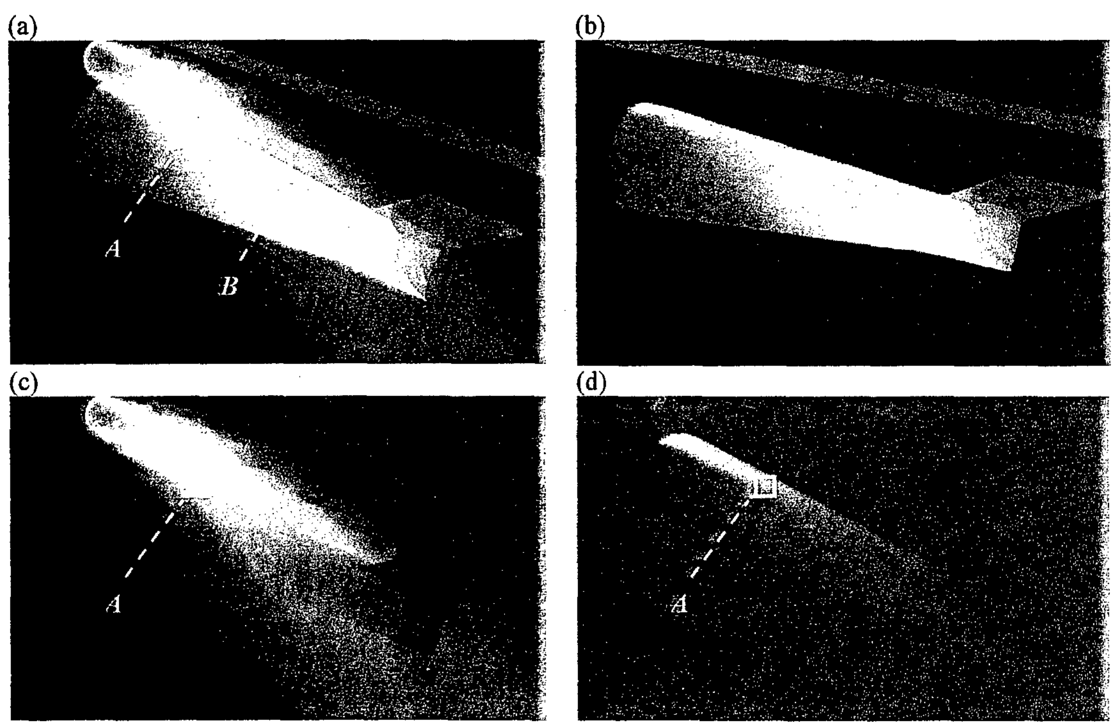

Figure 11 Radiant intensity images produced with McCavity (W sr^{-1}): (a) complete result, (b) view down onto the tail-boom with plume removed, (c) plume component only (d) reflection component only.

The spectral response obtained from the emission by a solid hot surface is expected to differ significantly from both the emission of a hot gas such as a plume and any reflected component of this. The reflected component would image the emission from the hot plume species at a reduced intensity determined by the surface reflectivity property.

To investigate the characteristics of the new high intensity region on the boom, the spectral response was taken between the wavelengths 4 and 5 microns for the regions shown in Figure 11, areas *A* and *B*. These were chosen to have the same image area of 91 pixels translating to an estimated target area of 2.08 m^2. *B* is located within the impingement-heated boom structure. *A* is taken from a region where both there is both a plume and reflection component, considered independently. The result is presented in Figure 12.

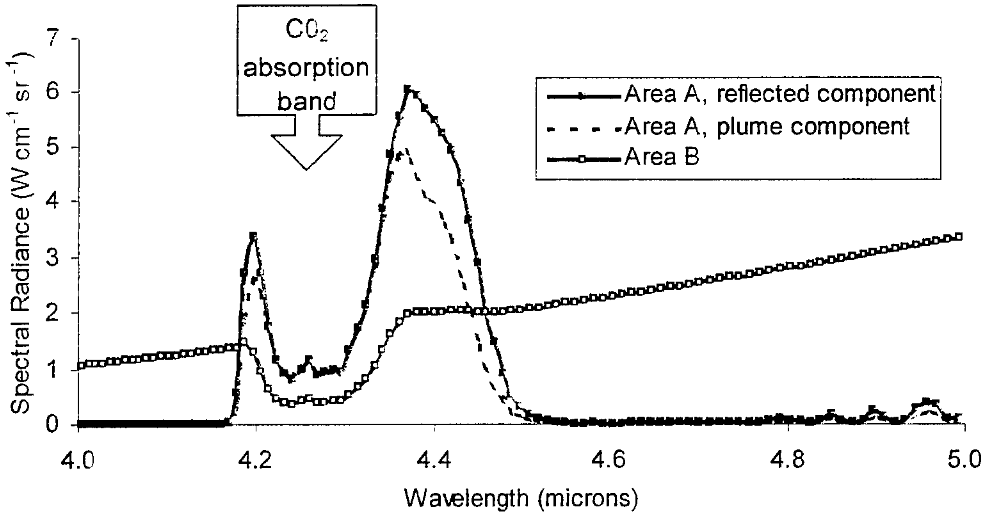

Figure 12 Spectral radiance of selected regions between the wavelengths of 4 and 5 microns.

A typical grey-body emission is obtained from area *B* as expected. This response has two contributing components, the presence of cool black body radiation, reduced by the emissivity of the surface, and some absorbance due to the species CO_2. This manifests as a dip in intensity between the wavelengths 4.20 μ to 4.37 μ. Both the reflected and plume component within area *A* show a completely different response. Significant radiance occurs only between the specific wavelengths of 4.17 μ and 4.50 μ, indicating the absence of continuum emission. This spectrally selective emission is characteristic of CO_2 fundamental (anti-symmetric stretch) gas emission. The signature arising from solely the reflected component is larger than the radiance from the emitted component. This has been calculated from the image with the plume removed. Consequently, there is no absorption of this signature. However, it demonstrates the potential for a significant reflection contribution even for a 50 % reflective, diffuse material.

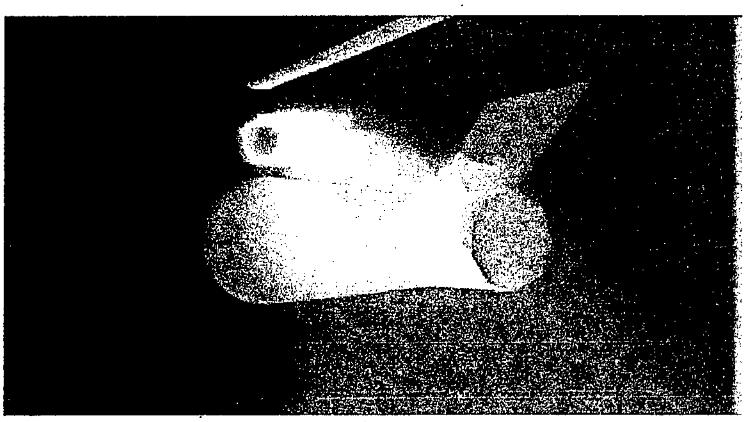

Figure 13 McCavity radiant intensity image (W sr^{-1}) showing a view of the rotor blade underside.

The image in Figure 13 takes a look-up view towards the underside of the rotor blade. This shows evidence of a signature component along the lower surface of the rotor blade. Comparison of this with Figure 10(d), which shows this thermal contribution was not previously present, therefore, confirms this as a plume reflection. This reflection would not suffer absorption from the plume due to its displaced position, potentially providing a high source of radiance.

This simple modelling example has successfully demonstrated the capability of McCavity to simulate reflections arising from the heated exhaust from a helicopter powerplant. Realistic structures are likely to be far more complex with many components acting as reflecting surfaces. The reflection contribution is highly dependent upon the target view, particularly for non-diffuse surface properties. Therefore, to fully assess the implications is a non-trivial exercise.

CONCLUSIONS

A Monte Carlo based ray tracing code, McCavity, has been developed, which can be used for modelling the reflection contributions to the infra red signature of targets.

Confidence has been shown in the calculation procedure through the successful comparison with published analytically derived solutions. The agreement level was well within the 1-2 % tolerance nominally expected from Monte Carlo processes for useful run times.

The application of McCavity to model reflection contributions from an extended hot gas source has been successfully demonstrated with a generic helicopter tail-boom and rotor structure using an unstructured CFD analysis. The importance of modelling extended source reflections has been shown and in some instances, such as rotor blade reflections, these have the potential of being significant.

ACKNOWLEDGMENTS

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